JTRP

Joint
Transportation
Research
Program

FHWA/IN/JTRP-97/12

Final Report

PART II

MANUAL OF THE INDIANA LANE MERGE CONTROL SYSTEM

A. Tarko
S. Kanipakapatnam
J. Wasson

May 1998

Indiana
Department
of Transportation

Purdue
University

Final Report

FHWA/IN/JTRP-97/12

Part II

Manual of the Indiana Lane Merge Control System

by

Andrzej P. Tarko
Professor

Sreenivasulu R. Kanipakapatnam
Resesarch Assistant

Jason S. Wasson
Research Assistants

Transportation and Infrastructure Systems
Department of Civil Engineering
Purdue University

Joint Transportation Research Program
Project No: C-36-75F
File No: 8-9-6

Prepared in Cooperation with the
Indiana Department of Transportation and
the U.S. Department of Transportation
Federal Highway Administration

Purdue University
West Lafayette, IN 47907
May 1998

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/IN/JTRP-97/12		

4. Title and Subtitle	5. Report Date
Modeling and Optimization of the Indiana Lane Merge Control System on Approaches to Freeway Work Zones	May 1998
	6. Performing Organization Code
7. Author(s) A. Tarko, S. Kanipakapatnam, and J. Wasson	8. Performing Organization Report No. FHWA/IN/JTRP-97/12
9. Performing Organization Name and Address Joint Transportation Research Program Purdue University West Lafayette, Indiana 47907-1284	10. Work Unit No.
	11. Contract or Grant No. SPR-2127
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204	13. Type of Report and Period Covered Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the Indiana Department of Highways and Federal Highway Administration.

16. Abstract

Severe traffic turbulence on entry sections of freeway work zones increases the delays and risk of crash. A new Indiana Department of Transportation system called Indiana Merge Lane System (IMLS) creates a dynamic no passing zone on the approach to the freeway work zone through the sequence of DO NOT PASS signs. The system is thought to encourage drivers to switch lanes well upstream of the discontinuous lane taper where the merging maneuver is safer and less intrusive. The IMLS is expected to impact drivers' behavior, their perception of the traffic conditions, and traffic safety.

This research is focused on: (1) drivers' compliance with the system, (2) delays and travel times on approaches to work zones, (3) optimal configuration of the system, and (4) warrants for the system's use. The simulation and field studies indicate a significant reduction in the number of merging maneuvers near work zones after the IMLS is applied. Also, the travel time on continuous lanes is reduced. The increased fairness of the system improves the perception of the traffic conditions among the majority of drivers. A slight reduction in the capacity of the merge point is the second finding of the field observations. This finding should be confirmed through long-term measurements of capacity during regular use of the IMLS units.

The final report is divided into two parts. Part I presents the performed research, including the simulation model development and simulation experiments. Part II contains the system description, guidelines for its use, and rules for its setting. The system description includes presentation of the concept and the system components. The guidelines for the system use provide the traffic conditions where the system is expected to provide benefit. Finally, the manual gives a set of simple rules useful in setting all the system parameters to achieve the maximum reduction in the travel time in the continuous lane.

17. Key Words	18. Distribution Statement
freeway work zone, traffic control, lane merge, simulation	No restrictions. This document is available to the public through the National Technical Information Service, Virginia, 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	128	

Form DOT F 1700.7 (8-69)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 CONCEPT OF THE INDIANA LANE MERGE SYSTEM

Each year in the United States transportation agencies are faced with the challenge of managing traffic in highway work zones. The biggest issues that need to be addressed with proper traffic management are the deterioration in traveler safety, excessive traveler delays, and negative impact on the surrounding areas. These problems occur mostly on the sections of roadway preceding the work zones in which one or more lanes are discontinued. These areas can typically be characterized by severe traffic turbulence resulting in increased accident risks and long traveler delays.

The entry section of the work zone is critical for traffic smoothness and safety because of the discontinuation of one or more lanes. Some drivers try to avoid dense traffic on the continuous lanes by approaching the work zone entry point in the discontinued lane up to the point where the lane change maneuver is difficult and risky. The aggressive lane changes resulting from such behavior create turbulence in the traffic stream, which negatively affects traffic performance. These negative effects include shock waves in the continuous lane, as well as the development of road rage among typically non-aggressive drivers. All of these effects create an extremely dangerous situation both at the merge point and within the work zone due to road rage, which continues far beyond the point at which the aggressive lane change takes place.

The Indiana Department of Transportation (INDOT) has undertaken an effort to implement a novel traffic control system at work zone entries. The system reduces the number of aggressive lane changes by encouraging drivers to switch lanes well upstream of the discontinuous lane taper. This allows drivers who are merging into the continuous lane to safely make the maneuver because of the increased headway between vehicles and the lower differential in speed between the two lanes. The system, which is called the Indiana Lane Merge System (ILMS), consists of a series of static and dynamic signs that create a variable no passing zone in advance of a multilane highway work zone (Figure

1.1). The signs are placed upstream from the taper adjacent to the discontinuous lane. The dynamic signs are activated by detectors down stream, which identify queuing at the approach to the work zone. The objective of the system is to provide a no passing zone that is longer than the queue.

This manual is intended to function as a stand-alone document for persons involved in the utilization of this system and is Part II of a two-part document developed as a result of research conducted by the Indiana Department of Transportation and Purdue University. Part II provides a brief explanation of the system's purpose, as well as guidelines regarding proper geometric layout and parameter settings of the system on rural two-lane freeways. Users interested in a more detailed explanation of the ILMS operation and research methodology should consult Part I.

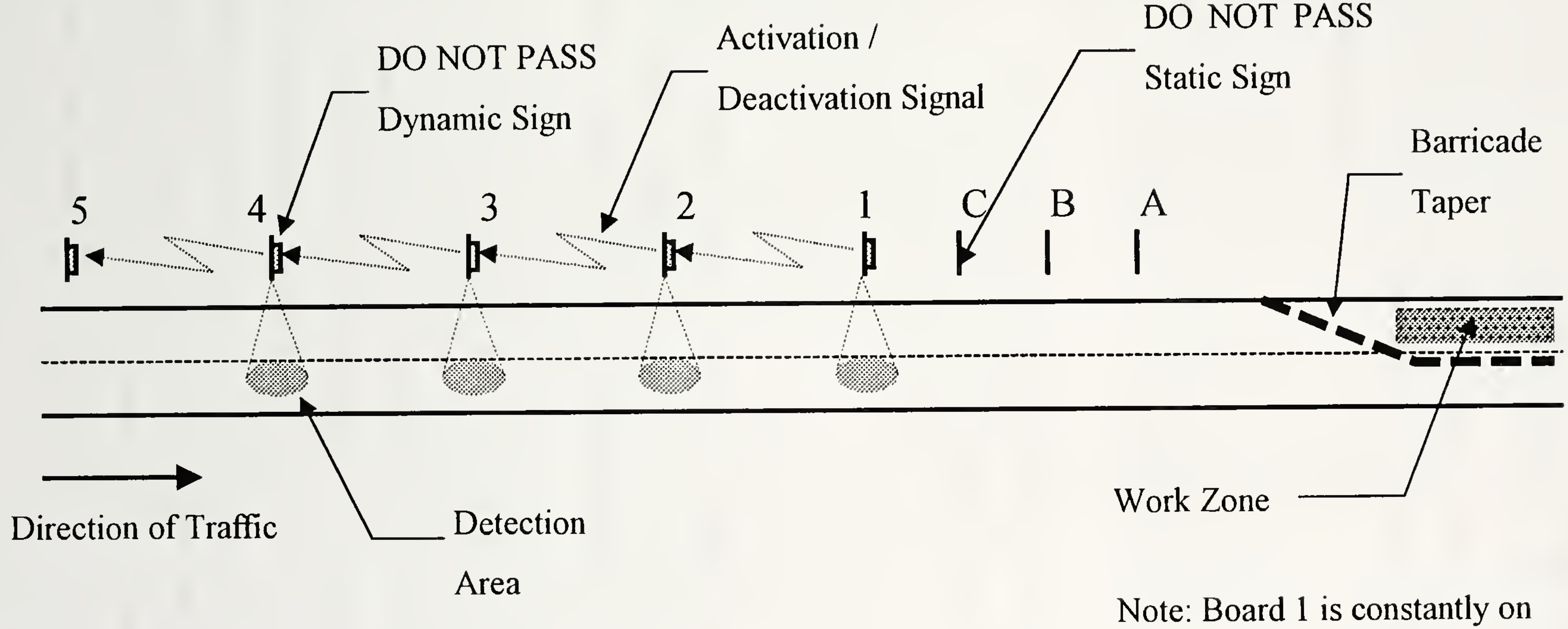


Figure 1.1 Concept of the Indiana Lane Merge System on Approach to Freeway Work Zone

2 ILMS COMPONENTS

The Indiana Lane Merge system can be an effective tool in stabilizing the traffic flow at the approach to work zones in which a lane is closed. This section provides a description of the system components.

The system consists of two types of signs. The first type is a static sign. The static sign has a white background and reads “DO NOT PASS” in black letters. The second type is a dynamic sign (see Fig. 1.2). The dynamic sign’s face consists of the following components:

1. Three panels vertically arranged on the support structure,
2. A series of solar panels which provide the required energy for the system,
3. Two solar powered strobe lights,
4. A radio receiver, and
5. A radio transmitter.

The top sign panel has an orange background and reads “WORK ZONE” in black letters. The remaining two panels have a white background with back text letters. The middle panel reads “DO NOT PASS” and the bottom panel reads “WHEN FLASHING".

There are three types of dynamic signs: *first*, *middle*, and *last*. The first dynamic sign is adjacent to the static signs and is the closest of the dynamic signs to the work zone. The middle dynamic sign follows the first dynamic sign in the upstream direction (opposite to the direction of traffic). The last dynamic sign is the sign farthest upstream from the work zone. This nomenclature was developed in terms of the order in which the building traffic queue would encounter the signs. All of the dynamic signs, except for the last sign, have a detector, which monitors occupancy of the traffic stream (Figure 1.3). The lights on the first dynamic sign are always on, thereby creating a constant no passing zone together with the three static signs. The static signs are there to remind drivers that

Figure 1.2 A Front View of the Dynamic Sign (shows sign face and strobe lights)

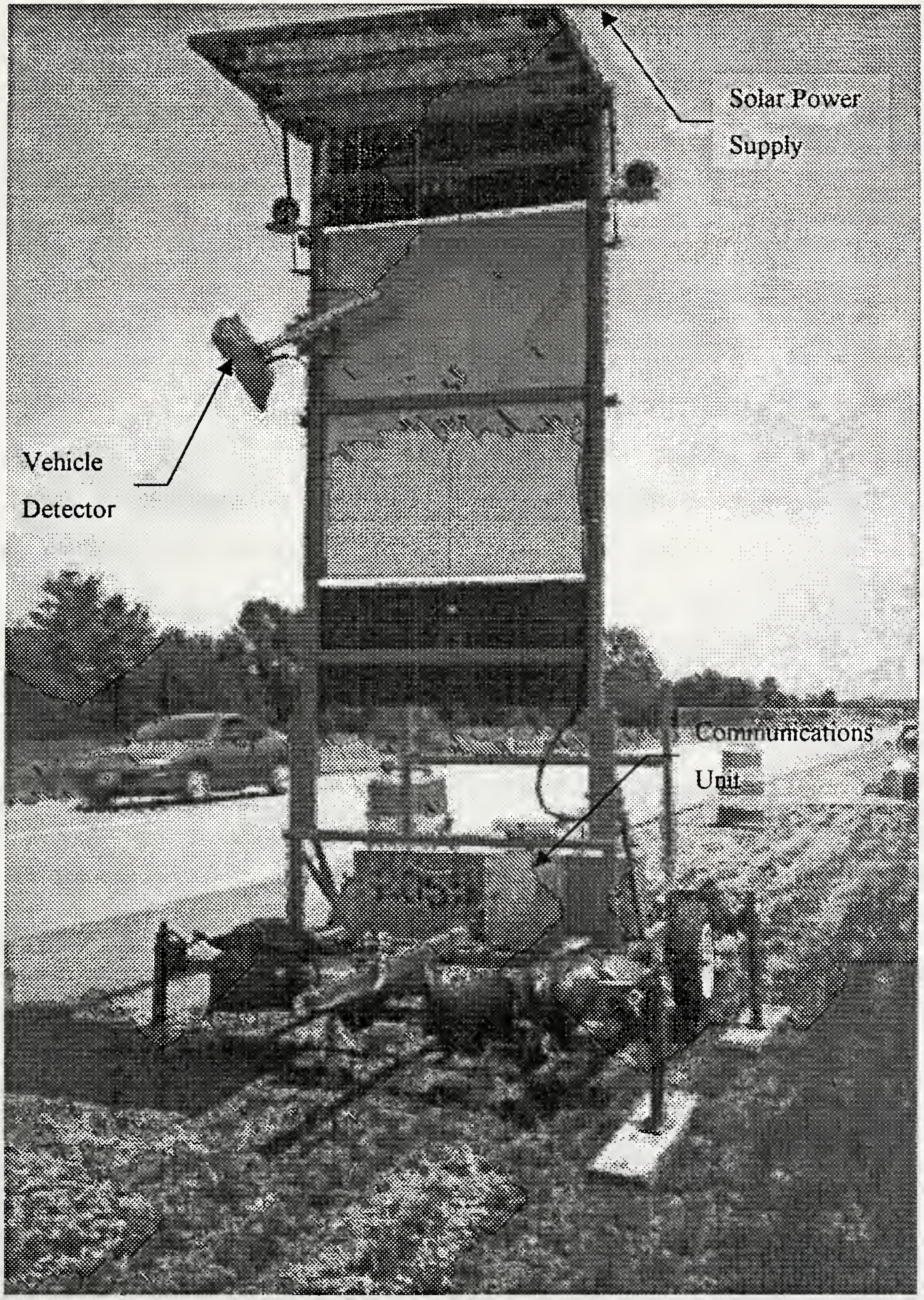


Figure 1.3 A Back View of the Dynamic Sign (shows sensor, communications box, and solar supply)

they are within this restricted zone. The primary operational rule for the activation of any of the dynamic signs is that a particular sign cannot be active unless all of the dynamic signs downstream have been already activated.

3 WARRANTS FOR USING THE SYSTEM

The ILMS mitigates the negative impact caused by aggressive drivers who utilize the discontinuous lane on work zone approaches at times when there is queuing traffic on the continuous lane. Because of this fact, the primary warrant for the system's use is the anticipated or observed presence of congestion at the entry point of the work zone. It is advised that the system be deployed if the congested segment is longer than 3 km. The maximum congested segment shorter than 1.5 km does not warrant the use of ILMS.

The maximum congested segment can be determined through direct observation or it can be estimated from work zone's capacity and traffic volume. The capacity of the work zone can be determined from Table 4.1 based on the type of activity planned in the work zone. Caution should be exercised in the determination of the traffic demand for the roadway segment during the time in which construction is in progress. This demand can be lower that the demand observed for the normal conditions since some drivers change route or time of travel. The availability of alternate routes can have a significant impact on the demand during the construction project. It is therefore recommended to observe traffic conditions at questionable locations one or two weeks after the construction project starts.

Section 4 describes in detail a method of determining the work zone's capacity, traffic volume, and a method of estimating the length of congested segment.

4 GUIDELINES FOR SYSTEM'S USE

The following rules apply to two-lane freeway work zones in which there are no interchanges in the immediate upstream vicinity of the work zone.

Once a need for IMLS has been decided, the geometric layout and system parameters must be determined. Following are the system settings:

1. The length of the deployment area,
2. The number of dynamic signs,
3. The spacing of the signs,
4. The threshold occupancy for activation of the dynamic signs,
5. The aggregation period for data collection, and
6. The minimum activation time for the sign.

The following sections discuss the steps necessary to determine these values.

4.1 Deployment Area

In order to determine the length of roadway over which the system should be deployed, it is necessary to determine the maximum queue length (length of congested segment, L_c). The overflow queue is the result of the demand exceeding the capacity of the work zone for some period. The length of congested segment can be determined from direct observation. In this case, the reader can skip Sections 4.1.2-4.1.6. Alternatively, the length of congested segment can be calculated using the procedure described below.

To calculate the maximum congestion length, the following values are needed:

1. Work zone capacity,
2. Traffic demand,
3. Unaffected density,

4. Congestion density,
5. Overflow queue.

The following sections provide a method of calculating these values.

4.1.1 Work Zone Capacity

The capacity for a particular work zone can be determined from Table 4.1 based on the type of the operation being performed. The shaded column represents the values associated with a two-lane freeway segment having one lane closed. The values have been established based on field observations that indicated a significant variation in capacities, even for the same type of operation (1,100 to 1,500 veh/h). Since many work zones in Indiana may consist of several of these operations, good engineering judgment is needed. The capacity measurement on I-69 in Indiana gave an average value of 1,450 veh/h for a bridge repair.

Table 4.1 Summary of Observed Capacities for Some Typical Operations (veh/h)
(Source: Highway Capacity Manual Table 6-2)

# of Lanes in One Direction					
Normal Operation	3	2	5	3 or 4	4
During Construction	1	1	2	2	3
Type of Work					
Median Barrier / Guardrail	---	1,500	---	3,200	4,800
Installation / Repair				2,940[a]	4,570[a]
Pavement Repair	1,050[a]	1,400	---	3,000	4,500
				2,940[a]	
Resurfacing, Asphalt Removal	1,050[a]	1,200	2,750	2,600	4,000
		1,300[a]		2,900[a]	
Striping, Side Removal	---	1,200	---	2,600	4,000
Pavement Markers	---	1,100	---	2,400	3,600
Bridge Repair	---	1,350[a]	---	2,200	3,400

[a] Texas data, full-hour capacities; all other data are from California, expressed in peak flow rates.

4.1.2 Traffic Demand

As mentioned in Section 3, substantial delays caused by the work zone results in some drivers seeking alternate routes or alternative travel times. Consequently, about two or three weeks after the work zone commences, the traffic demand stabilizes at a new lower level.

There are two possible options in designing the placement of the dynamic signs. In the first option, the system is set for the worst scenario of the first few days. The maximum length of congested segment is calculated based on the traffic volumes measured prior the construction zone. An inspection of the work zone is recommended after the first two or three weeks to determine a new maximum queue length from direct observations.

In the second option, the system is set for the new demand pattern. In this case, however, an analysis of alternative routes and even network-wide analysis may be required.

At work zones of prolonged duration, the placement of the boards must be updated to account for the seasonal changes in traffic volumes.

4.1.3 Unaffected Density

The unaffected density is the average density that would be expected at a particular volume level in the absence of the work zone. The Highway Capacity Manual provides a method to estimate the unaffected freeway density.

An approximated equation for Indiana two-lane rural freeways has been derived from the calibrated speed-density relationship (see Part I of the report):

$$D = 46.3 - \sqrt{2150 - 0.742 \cdot V} \tag{4.1}$$

where V = freeway volume during the last hour of the overflow period, veh/h.

The density obtained from Equation (4.1) applies to the traffic conditions better than the capacity conditions (LOS A-E).

4.1.4 Congestion Density

Congestion density is the average density of vehicles along the length of a congested segment. It is less than the jam density and greater than the average unaffected density. The average congestion density observed at two sites in Indiana is 71.6 veh/km. The traffic density in the continuous lane is 55.2 veh/h/lane, while in the discontinuous lane it is 16.4 veh/h/lane.

4.1.5 Overflow Queue

In order to calculate the length of a congested segment, the maximum number of vehicles accumulated at the entrance to the work zone must be known. The number of vehicles that cannot pass the lane drop is equal to the total number of vehicles that arrive during the overflow period (time when the demand exceeds the capacity) minus total capacity during the same overflow period. This value, called overflow queue, is represented by the shaded area in Figure 4.1.

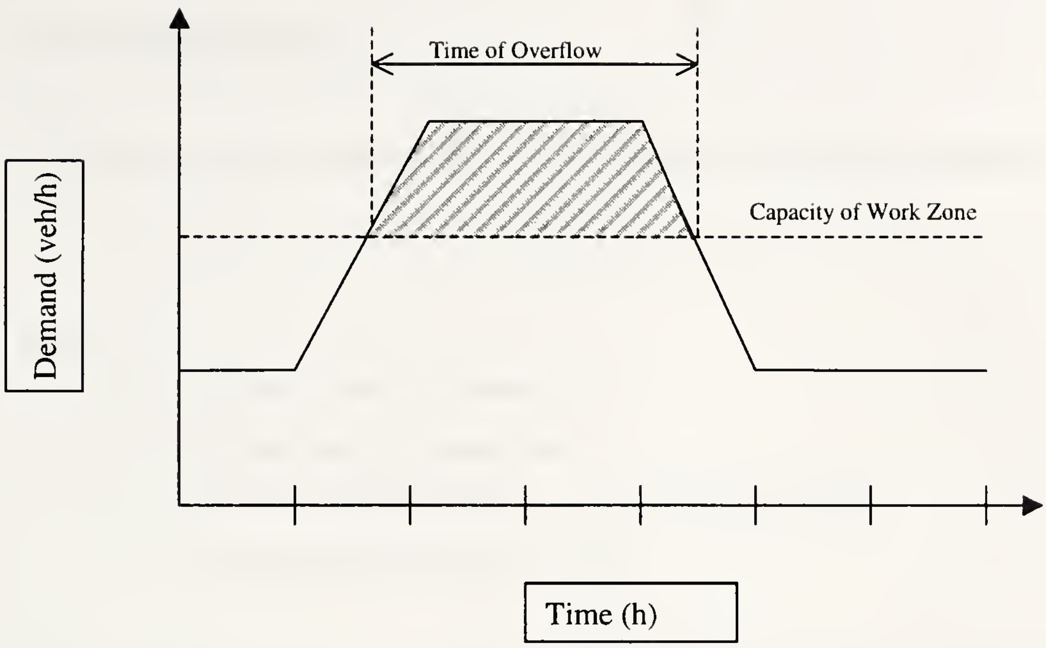


Figure 4.1 Traffic Demand, Work Zone Capacity, and Overflow Queue.

The overflow queue can be calculated using the following equation:

$$Q = \sum_{i}^{n} (V_i - C_i) \tag{4.2}$$

where:

Q = overflow queue, number of vehicles which accumulate during the overflow period,

V_i = demand in interval i experiencing overflow ($V_i > C_i$), veh/interval.

C_i = capacity during interval i, veh/interval,

n = number of intervals with overflow.

4.1.6 Congested Segment

The length of congested segment can be calculated using the following equation:

$$L_c = 0.92 \cdot Q/(D_c - D) \qquad (4.3)$$

where:

L_c = length of congested segment, km,

Q = maximum overflow queue, veh,

D_c = average congested density (in-queue density), veh/km,

D = average unaffected density, veh/km.

The denominator (D_c - D) account for the fact that the actual queue (sometimes called the horizontal queue) includes more vehicles than the overflow queue (sometimes called the vertical queue).

4.1.7 Length of Deployment Area

Where the deployment area is too short, a significant upstream portion of the queue stretches beyond the no-passing zone, reducing the effectiveness of the control. Where the deployment area is too long, then some upstream dynamic boards are activated only for a short period or not activated at all. This situation also reduces the effectiveness of the control. The deployment area, which gives the best performance of the control system, is calculated based on the congested segment, L_c:

$$d = 1.91 \cdot L_c^{0.56} \qquad \text{(km).} \qquad (4.4)$$

The value obtained from the equation represents a compromise between too short and too long deployment areas.

4.2 Number of Dynamic Signs

The maximum number of dynamic boards available for a single installation is six. The research has indicated that the maximum number of boards should be used if the congested segment is longer than 3 km. Two dynamic boards are recommended if the maximum congested segment is 1.5-km long. An intermediate number of boards (between 2 and 6) should be considered for the maximum congested segment between 1.5 and 3 km. It should be noted that a significant effect of ILMS is expected where the congested segment is longer than 3 km.

4.3 Sign Spacing

The minimum spacing between any two signs is 150 meters. This minimum distance is justified by considering the time and distance necessary for a driver to respond to any one of the signs.

The first board (Sign A in Fig. 1.1) should be located 150 m upstream of the taper of the work zone. The two remaining static boards (Sign B and Sign C in Fig. 1.1) should be placed with spacing of 300 m.. Thus, the third static boards should be 750 m upstream of the taper. This value can be reduced only where the length of the deployment area is insufficient to space the dynamic boards at the distance at least 150 meters.

The first dynamic sign (Figure 1.1) is always activated. It guarantees that the no-passing zone will be sufficiently long (0.6-0.9 km is desirable). This minimum requirement provides law enforcement officials with a sufficient distance to stop violators before they enter the work zone. This requirement was determined based on the comments from the Indiana State Police.

The spacing between consecutive dynamic boards should be uniform and determined from the following equation:

$$X = (d - d_s)/n \tag{4.5}$$

where: X = distance between the C and 1 boards, and between two consecutive dynamic boards, km,

d = deployment zone calculated from Equation (4.4), km,

d_s = distance between the third static sign (counting from the work zone) and the work zone taper, km,

n = the number of dynamic signs.

In the event, that X becomes less than 150 m, the spacing between the static boards can be reduced accordingly, but not below the required minimum of 150 m. Another option is to reduce the number of dynamic boards, particularly where six is originally considered.

4.4 Threshold Occupancy for Dynamic Sign Activation

The optimal threshold occupancy for the activation of the dynamic signs has been found to be 30 % for a typical detection zone of 1.8 meters. If the detection zone is much shorter than 1.8 m, the corresponding threshold occupancy in percentage can be determined as:

$$23 + 3.85 \textit{ detector length},$$

where *detector length* is expressed in meters. The research indicated that the system's performance does not change significantly with the change of the threshold occupancy if the threshold occupancy stays in the range between 25 and 35 percents.

4.5 Data Collection Aggregation Period

The minimum aggregation period is one minute. This value has been advised by the INDOT personnel based on their field observations. A shorter aggregation period would make the system too sensitive to short-term fluctuations in detector occupancies caused by traffic platoons. The aggregation period at least one minute long substantially reduces misinterpretation of platoons by the system as overflow queues. In the other words, this setting is thought to prevent premature sign activation.

If the aggregation period is too long, the system is sluggish in activating the upstream sign prior to the traffic queue building to that location. The value of five minutes seems to be a good compromise.

4.6 Minimum Activation Time

After activation, a dynamic sign stays on for at least a so-called "minimum activation time." This provision is thought to eliminate multiple activation and deactivation during a short period when the back of the queue reaches a detector. Due to the randomness, the detector occupancy fluctuates around the threshold value before it stabilizes at the value higher than the threshold. This setting has a similar function as the aggregation period and prevents the premature deactivation of signs.

The lower limit on the minimum activation time was set at one minute. On the other hand, a minimum activation time that is too long would cause an excessive delay in turning off the signs after the need for the no pass zone ends. The minimum activation time of five minutes seems to be a good compromise.

5 EXAMPLE CALCULATIONS

Calculate the length of deployment area for the ILMS on an approach to a work zone. The anticipated demand and capacity is given in the below table for half-an-hour intervals:

Beginning of interval	Traffic demand (veh/h)	Work zone's capacity (veh/h)
3:00	1300	1450
3:30	1490	1450
4:00	1600	1450
4:30	1650	1450
5:30	1500	1450
6:00	1300	1450

1) The unaffected density is calculated from the approximate equation (4.1):

   $D = 46.3 - (2150 - 0.742 \times 1500)^{1/2} = 14.10$ veh/km.

2) The maximum overflow queue is the difference between the total demand and the total capacity during the overflow period:

   $Q = 0.5 \times (1490+1600+1650+1500) - 0.5 \times 4 \times 1450 = 220$ veh.

3) The average traffic density D_c along the congested segment is 71.6 veh/km. The length of the congested segment is:

   $L_c = 0.92 \text{x} 220/(71.6 - 14.10) = 3.52$ km.

4) The length of the deployment area is:

   $d = 1.91 \text{x} (3.52)^{0.56} = 3.86$ km

5) Six dynamic "DO NOT PASS" boards are to be used. The spacing between them is:

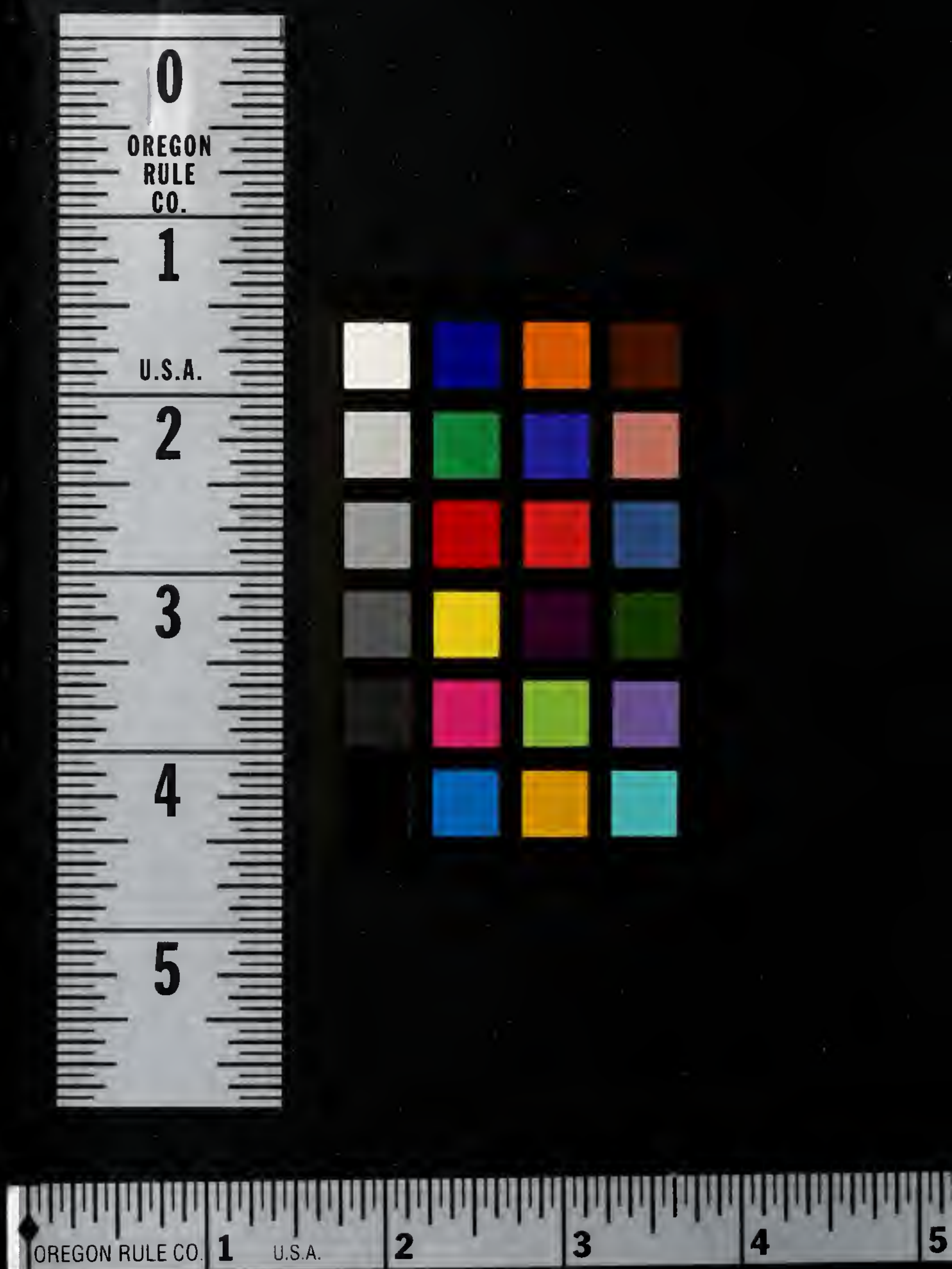
   $X = (3.86 - 0.75)/6 = 0.52$ km, $X = 520$ m > 150 m.

6) The maximum travel time can be calculated by dividing the total number of vehicles on the longest congested segment by the capacity rate of the work zone (outflow rate):

   $L_c D_c/C = 3.52 \times 71.6/1450 = 0.174$ h = 10.4 minutes.

The following settings are proposed for the considered work zone:

- Three static boards spread at the frequency of 0.15, 0.25, and 0.25 km
- Six dynamic boards spread at the frequency of 0.52 km
- Deployment area = 0.75+6x0.52 = 3.87 km
- Threshold occupancy = 30% for the 1.8-m detection zone
- Detector aggregation interval = 5 minutes
- Minimum activation time = 5 minutes


0
OREGON
RULE
CO.
1
U.S.A.
2
3
4
5
OREGON RULE CO.
U.S.A.